Springer

KSME

Journal of Mechanical Science and Technology 32 (10) (2018) 4839~4849
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-018-0932-z

Modeling and analysis of multi-shot injection molding of Blu-ray objective lens †

Min-Wen Wang[1], Chao-Hsien Chen[1], Fatahul Arifin[1,2,*] and Jian-Jr Lin[1]

[1]*Department of Mechanical Engineering, National Kaohsiung University of Science and Technology, Kaohsiung 80778, Taiwan*
[2]*Departement of Mechanical Engineering, Politeknik Negeri Sriwijaya, Palembang 30139, Sumatera Selatan, Indonesia*

(Manuscript Received January 8, 2018; Revised June 13, 2018; Accepted June 27, 2018)

Abstract

The Blu-ray objective lens is one of the electronic parts that has an important role in data storage in such a way that its production requires a high level of accuracy. One way to produce the Blu-ray objective lens is by means of a micro-injection molding technique. We investigated the effect of insert part in a multi-shot injection molding on the shrinkage after the process of injection. An aspherical shape is made for the insert part of the Blu-ray objective lens, then compared with single-shot injection molding. Zemax software was used to design the Blu-ray objective lens, while Moldex3D software was applied to analyze the flow of material into the mold during the injection process. The Taguchi method was used to determine the best parameters to obtain the minimum shrinkage values of the injection processes of both multi-shot injection and single-shot injection molding techniques. Based on the observations, it is clearly evident that the multi-shot injection molding process has a lower displacement value compared to the single-shot injection molding, namely, 0.0161 mm compared to 0.0550 mm and also the multi-shot injection can save the cooling time 5 seconds faster than single-shot injection molding. So, this can favorably improve the production of the injection process for the material in the form of the micro part.

Keywords: Blu-ray; Displacement; Multi-shot injection molding; Shrinkage; Single-shot injection molding

1. Introduction

Plastic processing is a relatively new branch of science and technology when compared to metal processing. However, at present, plastic products are widely used, especially for electronic parts such as projectors, mobile phones, and computers. The customers of plastic products demand widely diversified product lines and excellent quality. Thus, the production process of plastic products should take several parameters into account such as those related to geometry, weight, and quick production with good quality.

One piece of electronic equipment recently being developed and produced is the data storage system. A few years ago, people used compact disc (CD) and digital video disc (DVD) to store data, but recently they have switched to blu-ray disc (BD) as their data storage media. One of the reasons for this switch is that the Blu-ray disc is able to store five-times more data than that of DVD. The storage capacity of a Blu-ray disc ranges from 23.3 GB to 35 GB [1]. Blu-ray Disc requires a system that has a very high accuracy rate in order to read and store data; one of the most noteworthy parts in the Blu-ray disc system is the objective lens. This lens converts the laser beam into spots of small size; in other words, optical lenses will be able to read and write compact disc, digital video disc, and Blu-ray disc. This lens should also work well at 405 nm laser wavelengths, with a numerical aperture (NA) of 0.85 and 1.2 mm disk thickness with disk data-reading spacing of 0.1 mm from the cover layer [1, 2].

The Blu-ray objective lens is aspherical because with this form it can reduce the size and weight of the optical system as well as simplify the data storage system [2]. To meet the required functions, the objective lens should have very good geometric shape accuracy.

Plastic injection molding (PIM) is one of the most efficient and one of the major net-shape-forming processes for thermoplastics materials [3]. The types of plastic used in this production process are thermoset and thermoplastic, which are almost 32 % of all plastic consumption in the world [4]. The plastic injection molding process cycle is grouped by some researchers into three phases: Filling, packing and cooling [5, 6]. Many process parameters must be considered in the process of making optical lenses by means of plastic injection molding process in order to obtain an accurate geometric shape of the optical lens contour [7]. Injection molding of lens using plastic material with minimum variation in volumetric shrinkage is crucial for optical quality requirements; to predict the influence and optimal process parameters for minimum variation in volumetric shrinkage on injection molding of lens is more challenging [8].

*Corresponding author. Tel.: +886 908217400
E-mail address: farifinus@yahoo.com
† Recommended by Associate Editor Yongho Jeon

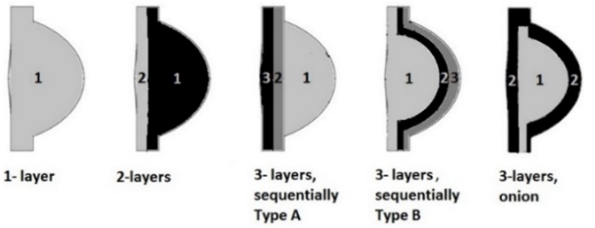


Fig. 1. Multi-shot injection molding strategies.

Defects commonly occurring during the injection molding process can be grouped into two types: those related to product dimension and those related to product quality. Levels of the factors affecting the injection process parameters are the temperature of the mold, followed by the melting temperature, the packing pressure and the injection speed. The relationship between injection and compression in the molding process, i.e., mold temperature, is the main factor influencing the shrinkage so that there is deviation of surface geometry profile of the optical lens product [9].

Previous studies have determined that a multi-shot injection molding technique can be employed to reduce defective factors that often occur in plastic injection molding processes, especially those related to precision, such as geometry, volume shrinkage in optical lens making. Multi-shot injection molding is the extension of the standard injection molding technology to allow for more components that can be simultaneously or sequentially injected together [10].

To have an accurate lens profile, the thickness of the last molded layer should be as uniform as possible to have uniform shrinkage during the cooling process. While to get the similar cooling effect at different layers, the thickness of different layers should follow Eqs. (1) and (2) [11] :

$$S_e\left(n\right)=\frac{2}{n+1}s_{total} \tag{1}$$

$$S_f\left(n\right)=\frac{1}{n+1}s_{total} \tag{2}$$

where s_e is the thickness of the first layer, s_f is the thickness of the next layer, and s_{total} is the total thickness of the part that will be produced by injection molding, n is the total value of layer [9]. Different strategies, such as one-sided multi-shot and two-sided multi-shot, can be applied to produce a plastic optical lens using multi-shot technology as shown in Fig. 1 [12].

Injection molding is the most efficient way to rapidly produce a plastic, aspherical Blu-ray objective lens, and multi-shot can provide better molding geometry accuracy of the lens

We first designed an aspherical lens that meets the Blu-ray requirement. Then we used molding simulation software (Moldex3D) together with Taguchi method to demonstrate that multi-shot molding of this lens will produce better surface accuracy.

2. Optical design

Blu-ray objective lens is a lens with high resolution. Accurate analysis requires taking the spot size and root mean square optical path difference (RMS_OPD) into account. Blu-ray read-write head systems use short wavelength lasers, and high numerical aperture (NA) values, which can reduce the spot size used for high-density data storage on Blu-ray disks. The blue laser beam passing through the objective lens may produce wave diffraction, so the beam may not fully focus to the same point. The actual spot size can be calculated corresponding to the following Eq. (3).

$$Z=\frac{0.61x\lambda}{NA} \tag{3}$$

where Z is the radius of the first dark ring, numerical aperture $NA = n \times sin\ \theta$, n is the refractive index of the lens, θ is the maximal half-angle of the cone of light that can enter or exit the lens, λ is the wavelength of the laser light.

The Strehl ratio is related to root mean squares-value of the wave-front aberration. This has an effect on the impact of deviations from the energy distribution, as shown in Eq. (4).

$$SR=e^{-(2\pi\omega)^2} \tag{4}$$

where $\boldsymbol{\omega}$ is usually the root mean square wave-front error in units of the wavelength.

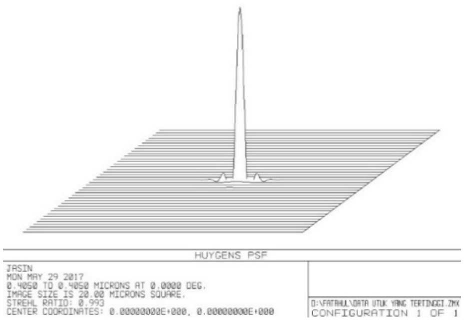
2.1 Blu-ray lens design

To reduce the size and weight of the optical system, the Blu-ray objective designed in this study is an aspherical lens instead of a spherical lens. The performance of an aspherical lens may be better than three to four spherical lenses [13]. The shape of the aspherical lens surface curve is calculated by Eq. (5).

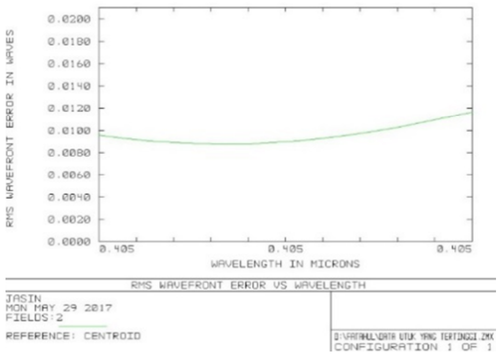
$$z(p)=\frac{\frac{p^2}{R}}{1+\sqrt{1-\left(1+k\right)\frac{p^2}{R^2}}}+\sum_{i=1}C_ip^{2+2i} \tag{5}$$

where $p=\sqrt{x^2+y^2}$ is the axial radius measured perpendicular to the z-axis and the z is the distance measured along the optical axis, R is the vertex radius, k is the conic constant, and C_i is the $(2+2_i)^{th}$ aspherical deformation constant [13, 14].

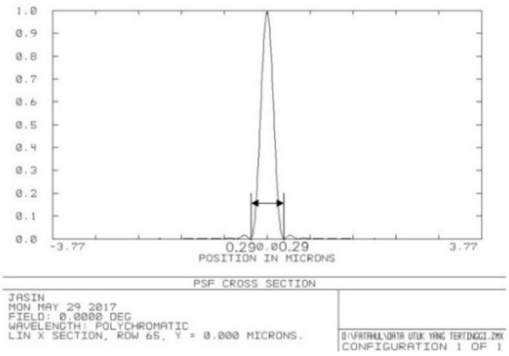
Zemax software is used in this study. Three steps are required to operate Zemax: 1) The size of primary lens design is entered into the software, 2) some parameters are defined as variables, and 3) the design specification is expressed as series of design goals called a merit function.



(a) Strehl ratio



(b) RMS_OPD



(c) Spot size

Fig. 2. The Zemax optimization results.

The merit function is defined as follows:

$$MF^2 = \frac{\sum W_i (V_i - T_i)^2}{\sum W_i} . \tag{6}$$

In Eq. (6) W_i is the weight of i^{th} operand, V_i is its computed value, T_i is the target value, and the summation is over all the operands in the merit function.

The following conditions are assumed: the Blu-ray lens has a maximum tilt of 0.1 degrees and uses 405 nm blue laser diode, and numerical aperture is 0.85, with 0.1 mm disc cover [1, 2], pupil entrance position is 5 mm, and the pupil entrance diameter is 4 mm. Then, the material used in this design is a clear-colored cyclic olefin copolymer (COC) TOPAS of grade 5013, with a heat-deflection temperature (HDT) / B 130 ^{o}C.

Table 1. Data of the Blu-ray objective lens.

Parameters	Surface I	Surface II
R	1.563150	-2.956634
K	0.567554	-99.891169
A4	0.007170	0.014238
A6	-0.000719	-0.003198
A8	0.000199	0.00327
A10	$2.157431E^{-11}$	$-7.77556E^{-11}$

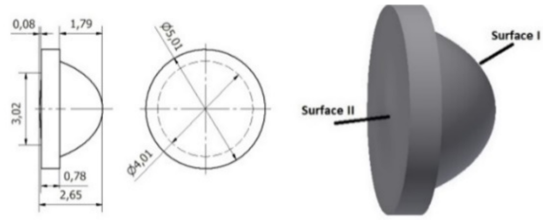


Fig. 3. Geometry of the Blu-ray objective lens.

This COC TOPAS 5013 is characterized by high flow capability and has excellent lens properties with a refractive index value of 1.53 and the Abbe number of 56.

The optimization results obtained from Zemax are spot size 0.58 μm, Strehl ratio 0.993, and root mean square optical path difference (RMS OPD) < 0.018 λ as shown in Fig. 2.

Meanwhile, the best optical objective lens design results to meet the calculation requirements using Eqs. (3) and (4) are: Spot size of 0.58 μm, Strehl ratio of 0.993 and root mean square optical path difference (RMS OPD) < 0.033 λ and the geometry of the Blu-ray lens is 2.65 mm of total thickness, 0.909 mm of working distance, and edge thickness of 0.78 mm (Fig. 2). The parameters of the double-side aspherical-lens obtained by Zemax optimization can be seen in Table 1.

The geometry of Blu-ray objective lens is 2.65 mm of the total thickness, 0.909 mm of working distance, 0.78 mm of edge thickness (Fig. 3).

3. Mold design and injection molding simulation

3.1 Mold design

Designing a Blu-ray objective lens mold needs to comply with several criteria. The runner system shown in Fig. 4 is designed for future molding of the lens using a Battenfeld Microsystems 50, which is a machine gain with the smallest component in the one-digit milligram range.

The gate is the door to the mold cavity; the melt flows into the cavity through the gate. The gate designed for this lens molding is a side-shape gate called the lateral gate, which has a rectangular cross-section dimension of 0.25 mm x 1 mm for the inert molding and dimension of 0.5 mm x 1 mm for the 2nd shot and the one-shot moldings (Fig. 4).

The method of three-layer onion multi-shot molding was chosen in this study. The Blu-ray objective lens inserts part is

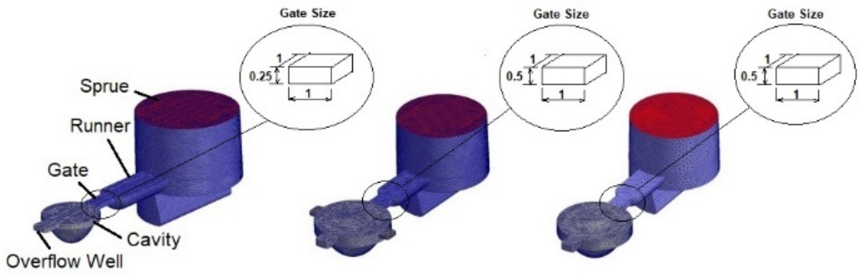


Fig. 4. Mold designs of Blu-ray objective lens: (a) Insert part of multi shot; (b) multi shot; (c) single shot.

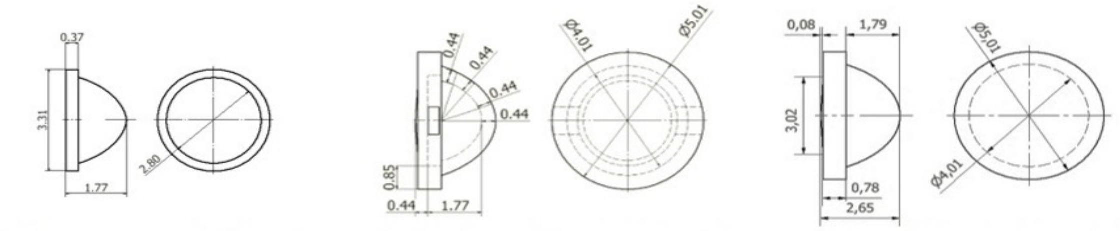


Fig. 5. Cavity designs of Blu-ray objective lens: (a) Insert part of multi shot; (b) multi shot; (c) single shot.

designed with double aspherical shapes. Using Eqs. (1) and (2), where the total part thickness is obtained with the Zemax software of 2.65 mm, the insert part thickness of 1.77 mm is obtained. The cavity designs of the Blu-ray objective lens can be seen in Fig. 5.

3.2 Injection molding simulation

We used Moldex3D to analyze the mold filling process. The material for molding the aspherical lens is an optical grade Topas COC 5013, the recommended processing parameters from the Topas are melt temperature 250 °C – 300 °C, mold temperature 95 °C – 130 °C, and ejection temperature 133.85 °C.

4. Design parameter analysis

4.1 Overview of parameter designing process

Many researchers, such as Oktem et al. [15], used the Taguchi method in injection molding to find the best processing parameter combinations and the effects of control factors on the molding qualities. Oktem et al.'s work showed that shrinkage and warpage could be significantly improved by about 0.7 % and 2.1 %, meaning that the Taguchi method manages to reduce product shrinkage and warpage effectively.

Lee and Lin [16] and Erzurumlu and Ozcelik [17] applied melt temperature, mold temperature, packing pressure, holding time and cooling time as control factors, then used the Taguchi method and finite element analysis to improve the qualities of their injection molding parts. Their results showed that the melt temperature is the most influential processing parameter.

Based on the previous studies, it can be concluded that processing factors affecting the injection molding quality most are mold temperature, material temperature, injection pressure, holding pressure and holding time.

Besides the optimal design of the aspherical Blu-ray objective lens, another purpose of this study was to demonstrate that recent developed multi-shot molding technology can be applied to produce this aspherical Blu-ray objective lens with better molding quality than with traditional single-shot molding. Taguchi's optimization technique is a unique and powerful optimization discipline that allows optimization with a minimum number of experiments. The Taguchi experimental design reduces cost, improves quality, and provides robust design solutions. Its advantages over the other methods are that numerous factors can be simultaneously optimized, and more quantitative information can be extracted from fewer experimental trials [18]. So, the Taguchi experimental method was implemented to find the best combination of molding injection process parameters for both the multi-shot injection molding and the single-shot injection molding of Blu-ray objective lens as well as the lens molding qualities.

4.2 Designing the processing window

Before performing the injection molding simulation process, the processing parameters of the selected material should be set first, then determine the ranges and levels of the control factors for the Taguchi experiments.

For the aspherical Blu-ray objective lens to function properly, the molded lens should have good form accuracy. War-

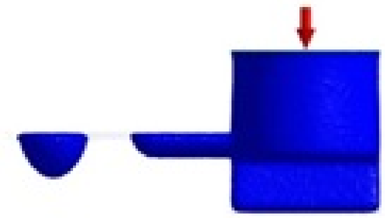


Fig. 6. The gate was frozen at 0.31 s.

page and shrinkage are the two main reasons affecting the molding part accuracy. Proper mold temperature can reduce the molded-in residual stress and shrinkage in the polymer lens production [19]. Higher mold temperature would lessen the rapid cooling effects of polymer melt inside the mold cavity. Hence, the molded lenses can be better packed into higher form accuracy lens production [20]. The melt temperature is a significant factor that affects the shrinkage of the lens production [21]. The higher the melt temperature, the higher the shrinkage when it is cooled, but it also allows effective packing that reduces shrinkage. Packing pressure control plays an important role in quality of injection molding productions [22]. Packing pressure is applied after the filling process and before the melt in the gate is frozen to compensate the melt shrink. Packing is important especially for nonuniform thickness parts like the aspherical lens studied here; it is critical to achieving high accuracy lens production [20].

Among those molding parameters, the mold temperature, melt temperature, and packing pressure each has a significant influence on the part warpage and shrinkage qualities. Thus, these were selected here as control parameters in the Taguchi experiment.

4.2.1 Packing time and cooling time

For the multi-shot process, the inner layer (insert) of the lens was molded and cooled first; then was placed in the cavity of the 2nd shot (outer layer of the lens) as an insert, the 2nd shot was over-molded over the insert.

Except for the parameters selected in the Taguchi experiment, other molding parameters such as packing time, cooling time, and injection speed have to be determined. From the Moldex3D simulation, it was found that the melt in the gate area solidified at 0.31 seconds for the inner layer molding as shown in Fig. 6. At the same time, the difference in melt temperature between the inside, the center of the cavity, and outside the part wass about 41.5 °C according to the observation. Too much difference in part after cooling will cause the part to shrink from inside and easily have sink mark or void defects in the lens.

After 5 seconds cooling, the temperature reduced to less than 1 °C, which is 112.28 °C in the center and is 111.78 °C at the outer edge of the lens as shown in Fig. 7. Then the cooling time was fixed at 5 seconds in the Taguchi experiments.

The gates for the multi-shot 2nd shot and the single shot parts are of the same size and are bigger than the gate of the

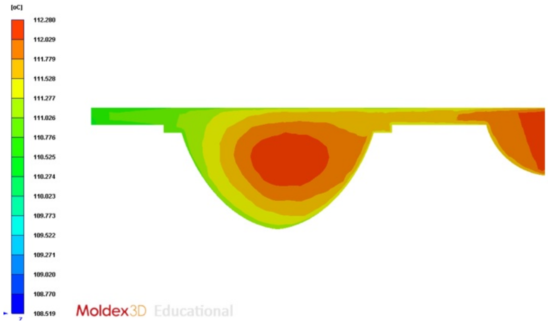


Fig. 7. Melt temperature distribution after 5 seconds cooling for the insert.It was until after cooling for 20 seconds both cases had melt temperature less than 1 °C, inside 110.011 °C and outside 110.011 °C for the 2nd shot, inside 111.997 °C and outside 111.781 °C for the one-shot case. So, the cooling time for both cases was set for 20 seconds.

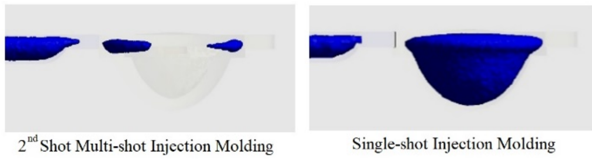


Fig. 8. The gate starts to freeze at the 0.56 s.

insert part as shown in Fig. 4. From the Moldex3D simulation again, the gate was frozen at 0.56 seconds for both cases as shown in Fig. 8. After 0.56 seconds packing, the melt temperature difference between inside and outside of the part was 49.4 °C (160.35 °C inside and 110.98 °C outside) for the 2nd shot case and 67.1 °C (179 °C inside and 111.9 °C outside) for the one-shot case. The 2nd shot was thinner and smaller than the one shot, so as it cooled quicker than the one-shot case.

4.2.2 Injection speed

In the injecting process, the melt was pushed into the cavity by the injection screw or the injection plunger. The normally higher flow rate needs higher injection pressure to fill the cavity, but the polymer is a non-Newtonian fluid; the shear thinning effect tends to decrease the viscosity of the melt at high injection speed. Stress induced by the filling process also has a big influence on the plastic part birefringence, which affects the optical performance of the molded lens. Simulation with different injection speeds was carried out prior to the Taguchi experiment to find the proper injection speed that had lower injection pressure as well as birefringence for the three cases. Injection speed ranges from 5 mm/s to 50 mm/s were tried in order to find the speed to have both low injection pressure and birefringence. From the results shown in Fig. 9, the injection pressures and birefringence have the lowest values at 10 mm/s and 15 mm/s, respectively. For the 2nd shot and one-shot cases, 15 mm/s provides a better combination of injection pressure and birefringence. Therefore, the injection speed for all injection molding cases was set to 15 mm/s for the Taguchi experiments.

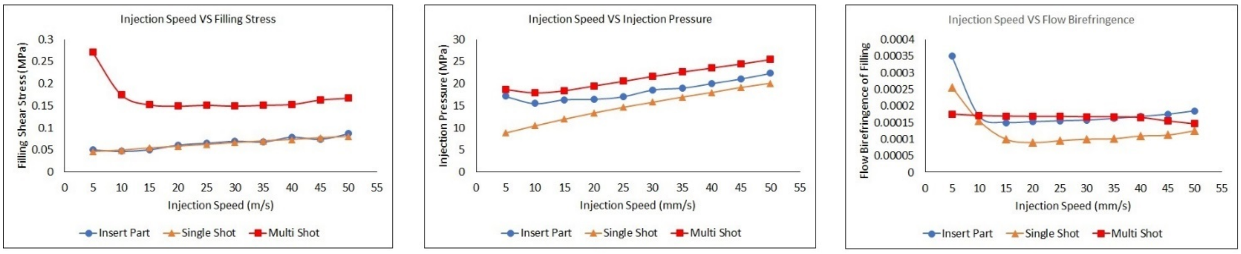
Table 2. The levels of the control factors in the Taguchi experiments for all injection molding process.

	A (°C)	B (°C)	C (MPa)
Level 1	95	255	55
Level 2	110	265	60
Level 3	130	275	65

Factors: A = T_{MOLD}, B = T_{MELT}, C = P_{PRESS}

Table 3. The fixed parameters.

Injection process	Fixed parameters		
	Injection speed (mm/s)	Cooling time (s)	Packing time (s)
Insert part	15	5	2
Multi-shot injection molding	15	20	3
Single-shot injection molding	15	20	3



(a) (b) (c)

Fig. 9. Different molding qualities vs injection speed.

4.3 The control factors

To have the best optical function from the aspherical Blu-ray objective lens, the molded lens should have as close to the contour as designed. In this study, the Taguchi experiment wase implemented to find the best processing parameter combinations for the insert molding, the 2nd shot (outer layer), and for the single shot lenses. Observing nodes were selected to perceive the shape accuracy of the Blu-ray objective lens and to recognize the parameter influences on the molding quality. The total displacement of the nodes before and after molding can be an indicator for the lens form accuracy, and it is the smaller-the-better (STB) quality feature. The signal to noise (S/N ratio) of the smaller-the-better is defined [23] as:

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i-1}^{n} y_i^2\right)(dB) \tag{7}$$

where y_i: displacement of Node *i*, *n*: number of samples.

The three control factors selected in this Taguchi experiment are mold temperature (T_{MOLD}), material temperature (T_{MELT}), and packing pressure (P_{PRESS}) , each with three levels, so L_9 (3^3) orthogonal array was chosen. The parameter levels for the three control factors are listed in Table 2. Other injection process parameters that remained fixed in these experiments are injection speed, packing time, and cooling time as shown in Table 3.

The response variable chosen for optimization was the total displacement (TD) value, then selecting criterion was "smallest is the best" for this analysis.

5. Results and discussion

5.1 The result of taguchi method simulation experiments

After the simulation was run with Moldex3D, the coordinate data before injection molding (x_0, y_0, z_0) and after injection molding (x_1, y_1, z_1) were observed at all points (overflow well (OW), up (UP), bottom (BT), and far from the gate (FG)) as shown in Fig. 10, and the displacement (Disp.) for each observing node can be calculated using the formula below:

$$Disp. = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2}\ . \tag{8}$$

Each lens has two surfaces, surface I and surface II, and the averaged displacement of the two surfaces represents the distortion of the Blu-ray objective lens molded in this experiment. Smaller displacement means smaller distortion of the lens. This result was also used to calculate the S/N ratio of the Taguchi experiment. Using ANOVA, the contribution of the control parameters could be determined.

The results of the displacement of the insert part of multi-shot injection molding, multi-shot injection molding, and single-shot injection molding of Blu-ray lens are in Table 4, and the S/N response is in Fig. 11. ANOVA results are summarized in Tables 5-7.

In Fig. 11(a) the best combination of the insert part of multi-shot injection molding is A1B2C1, the best combination of single-shot injection molding is A1B2C1 (Fig. 11(b)), and finally the best combination of 2nd shot multi-shot injection molding is A1B1C1 (Fig. 11(c)).

The experimental results for the insert part (1st shot of multi

Table 4. Taguchi design and results of all injection molding process.

Level	A	B	C	Insert part multi-shot injection molding		Multi-shot injection molding		Single-shot injection molding	
	ºC	ºC	MPa	Average (mm)	S/N	Average (mm)	S/N	Average (mm)	S/N
1	95	255	55	0.0145	36.773	0.0187	34.563	0.0557	25.083
2	95	265	60	0.0159	35.972	0.0233	32.653	0.0560	25.035
3	95	275	65	0.0138	37.196	0.0214	33.392	0.0572	24.859
4	110	265	55	0.0119	38.511	0.0279	30.088	0.0562	25.006
5	110	275	60	0.0192	34.343	0.0192	34.334	0.0689	23.235
6	110	255	65	0.0165	35.650	0.0307	30.257	0.0629	24.024
7	130	275	55	0.0242	32.342	0.0217	33.254	0.0551	25.173
8	130	265	65	0.0186	34.633	0.0293	30.657	0.0698	23.120
9	130	255	60	0.0226	32.933	0.0320	29.903	0.0723	22.820
Mean (m)					35.373	-	30.788	-	24.261

Factors: A = T_{MOLD}, B = T_{MELT}, C = P_{PRESS}

Table 5. ANOVA insert part (1st shot multi-shot injection molding).

Factor	Sum of squares (SS)	f DOF	V variation	S' pure change	ρ contribution (%)
A	19.624	2	9.812	19.624	60.727
B	4.858	2	2.429	4.858	15.033
C	4.120	2	2.060	4.120	12.750
AB	1.173	4	0.293	1.173	3.629
AC	0.458	4	0.114	0.458	1.416
BC	0.335	4	0.084	0.335	1.037
ABC	0.391	6	0.065	0.391	1.209
e (error)	1.356	-	-	1.356	4.197
T (error)	32.315	24	14.301	-	100.000

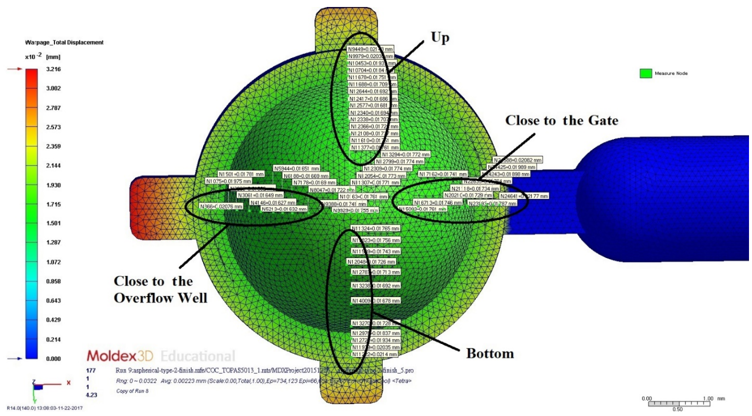
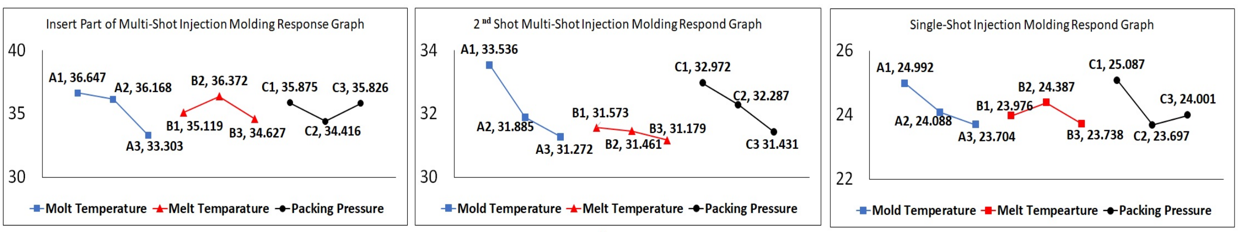


Fig. 10. Observing points of the part in Moldex3D simulation.



(a) (b) (c)

Fig. 11. Main effects plot for S/N ratio of injection molding process.

Table 6. ANOVA multi-shot (2nd shot) injection molding.

Factor	Sum of squares (SS)	f DOF	V variation	S' pure change	ρ contribution (%)
A	8.213	2	4.106	8.213	32.121
B	9.165	2	4.583	9.165	35.846
C	3.581	2	1.790	3.581	14.005
AB	0.525	4	0.131	0.525	2.052
AC	0.395	4	0.099	0.395	1.546
BC	0.165	4	0.041	0.165	0.644
ABC	1.573	6	0262	1.573	6.155
e (error)	1.951	-	-	1.951	7.630
T (error)	25.568	6	10.479	-	100.000

Table 7. ANOVA single-shot injection molding.

Factor	Sum of squares (SS)	f DOF	V variation	S' pure change	ρ contribution (%)
A	2.624	2	1.312	2.624	34.955
B	0.370	2	0.185	0.370	4.932
C	3.206	2	1.603	3.206	42.712
AB	0.176	4	0.044	0.176	2.339
AC	0.357	4	0.089	0.357	2.275
BC	0.171	4	0.043	0.171	7.016
ABC	0.527	6	0.088	0.527	1.016
e (error)	0.309	-	-	0.309	1.852
T (error)	7.506	6	3.100	-	100.000

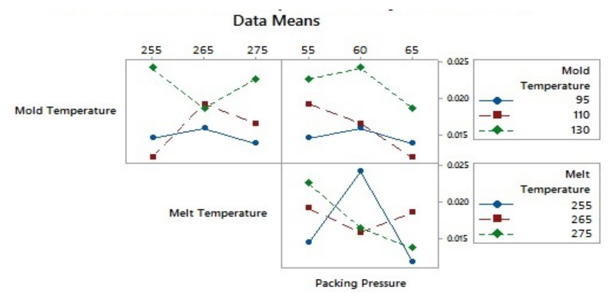


Fig. 12. Interaction effects plot data means for insert part (1st shot) multi-injection molding.

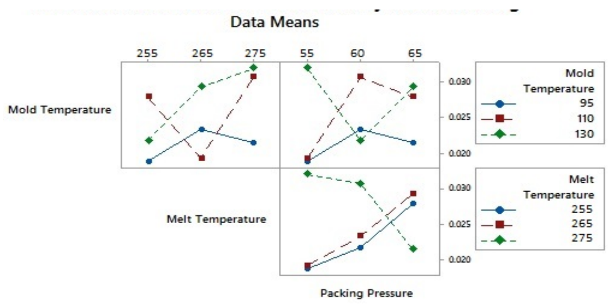


Fig. 13. Interaction effects plot data means for (2nd shot) multi-injection molding.

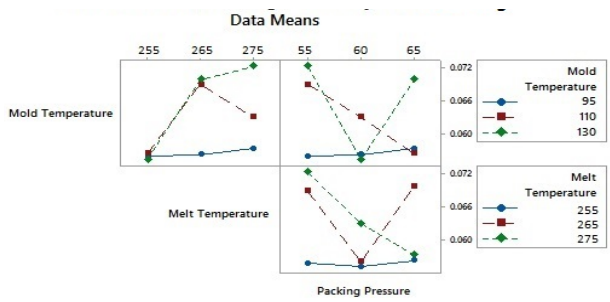


Fig. 14. Interaction effects plot data means for single-injection molding.

shot injection molding) are listed in Table 5. Mold temperature contributed the highest percentage of the displacement. Mold temperature influences the difference in temperature between the outside temperature and inside temperature (core temperature), and also there is a decrease of melt temperature at the end of injection, so the flow of material becomes inhabited into the cavity, then packing pressure just gives a little effect due to the decline in temperature especially at the tiny gate area that makes the material demold quickly. The percentage of mold temperature is (60.727 %), followed by melt temperature (15.033 %) and packing pressure (12.750 %).

The results for the 2nd shot of multi-injection molding are in Table 6. It shows that melt temperature contributed the highest percentage (35.846 %) to the displacement, followed by mold temperature (32.121 %), and packing pressure (14.005 %). As is known in 2nd shot multi-injection molding, the insert part is put in the cavity before injection, so the differences in temperature between outside and the core are high. When the end of injection the temperature decreases, so the outside and core

Table 8. The best displacement of injection molding process [mm].

Multi-shot injection molding					Single-shot injection molding				
OW	UP	BT	CG	Average	OW	UP	BT	CG	Average
0.0156	0.0159	0.0159	0.0163	0.0161	0.0545	0.0551	0.0552	0.0553	0.0550

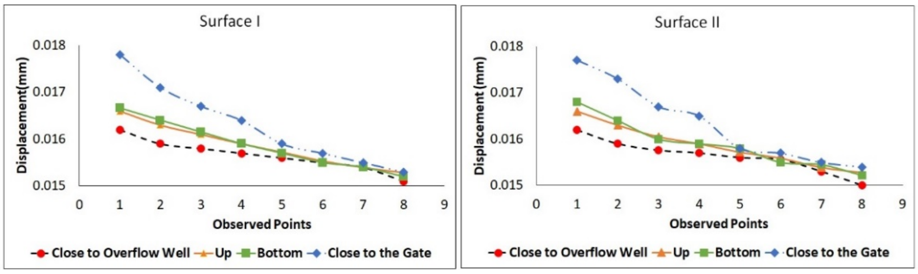


Fig. 15. Multi-shot injection molding displacement graph.

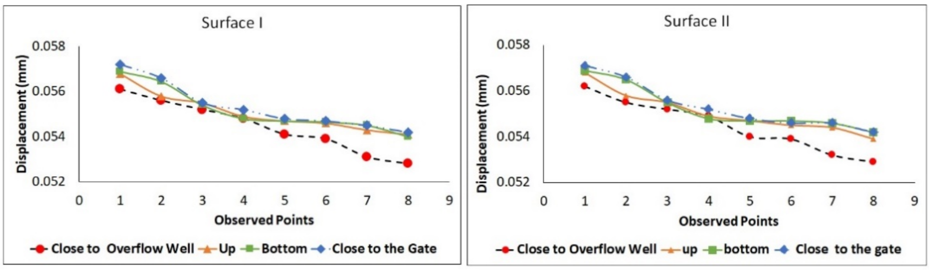


Fig. 16. Single-shot injection molding displacement graph.

temperature are relatively the same, however, the flow of material becomes inhabited into cavity due to the tiny area, then the packing pressure only has a little effect to the cause of the decreasing temperature.

The results for the single shot multi-injection molding are in Table 7. Results indicated that packing pressure contributed the highest percentage (42.712 %) to the displacement performance, followed by mold temperature (34.955 %) and melted temperature (4.932 %). Because the cavity area of a single shot is thicker than insert part (1st shot) multi shot injection molding, the material flows more easily to the cavity. The packing pressure after the end of injection could have more effect on the material due to the difference between outside temperature and core temperature, so still possible to flow material into the cavity.

There is always an interaction between molding parameters on the molding qualities. The interaction plots shown in Figs. 12-14 indicate that there indeed are interaction effects on the displacement performance of the three Taguchi experiments. According to the ANOVA results in Tables 5-7, the interaction between mold temperature and melt temperature has the highest contribution, 3.629 %, to the displacement performance in the inert molding, while the interaction between all three factors has the highest contribution, 6.155 %, in the 2nd shot molding, and the interaction between melt temperature and packing pressure has the highest contribution at 7.016 % for the single shot case. The contributions from interaction are not very high compared to the contribution from dominant factors in all three cases in this study.

5.2 Optimal form accuracy results

After obtaining the best combination of injection process parameters using the Taguchi experimental method, the simulation was executed again to obtain the optimum displacement value. The best displacement performances for the multi-shot and single shot are 0.0161 mm and 0.055 mm, respectively. The multi-shot result represents the multi-shot molding final performance, and it has improved the form accuracy dramatically. It can be concluded that multi-shot molding will have better molding qualities than the single shot molding.

According to the displacement results shown in Figs. 15, 16 and Table 8 of the observing points, the displacements are not the same in a different area and at different positions since the melt at different locations go through different P-v-T histories during the molding process. In the area close to the gate, we can expect less shrinkage than the area close to the overflow well, but higher frozen in residual stress causes bigger warpage near the gate for this micro lens molding, so the displacement near the gate is bigger than that far from the gate, that is close to the overflow well.

5.3 Cooling time

According to the time needed to freeze the product, where the differences in the temperature inside and outside are less than 1 °C. To complete the multi-shot molding of this lens, the cooling times added-up will be 15 seconds, 1st shot 5 seconds and the 2nd shot 10 seconds. While it takes 20 seconds for the one-shot lens, the multi-shot injection molding is faster than the single-shot injection molding, namely, 5 seconds. If a multi-shot molding machine and a rotation mold with both insert and the 2nd shot cavities were used to produce this lens, the insert and the 2nd shot would be molded at the same time, which will reduce the overall molding cycle time further.

6. Conclusions

The shape of an aspherical lens is not the same as a normal spherical lens; it's also lighter and flatter than the spherical lens and saves material. A double side's aspherical lens was designed in this study using the optimal design function of Zemax software. The lens has a spot size of 0.58 μm, a Strehl ratio of 0.993, and a root mean square optical path difference < 0.018 λ that matches the requirements of a Blu-ray objective lens. Instead of the typical injection molding process, we propose molding this lens un-uniform thickness distribution lens using multi-shot molding process. Mold filling simulation results revealed that a two-shot multi-shot molding could dramatically improve the lens from accuracy as well as save the cooling time. If a multi-shot molding machine and a rotation mold with both insert and the 2nd shot cavities were used to produce this lens in industry, the insert and the 2nd shot would be molded at the same time; that will reduce the overall molding cycle time further. Molding simulation was implemented to demonstrate the benefits of multi-shot molding of the uneven thickness lens designed; further molding of this lens with a Battenfeld Microsystem 50 micro molding machine will be carried out to verify the results reported in this paper.

Acknowledgments

This work was supported by the Ministry of Science and Technology (MOST) Taiwan under the grant of MOST 105-2221-E-151-067. The financial support is acknowledged.

References

[1] D. Chen, D. Chen and B. Wang, The advantages of Blu-ray disc, *Proc. SPIE,* 5966 (2005) 1-5.

[2] M. Nobuyoshi, K. Tohru, T. Kyu, H. Junji, O. Yuichiro and M. Nobuo, Plastic objective lens for Blu LD optical pick up, *Konica Minolta Technology Report,* 2 (2005) 153-156.

[3] W. Guo, L. Hua, H. Mao and Z. Meng, Prediction of warpage in plastic injection molding based on design of experiments, *J. of Mechanical Science and Technology*, 26 (4) (2012) 1133-1139.

[4] A. Mamat, T. F. Trochu and B. Sanschagrin, Analysis of shrinkage by dual Kriging for filled and unfilled polypropylene moulded part, *Polymer Engineering and Science*, 35 (19) (1995) 1511-1520.

[5] K. M. Tsai, C. Y. Hsieh and W. C. Lo, A study of the effect of process parameter for injection molding on the surface quality of optical lenses, *Material Processing Technology*, 209 (2009) 3469-3477.

[6] S. Kitayama and S. Natsume, Multi-objective optimization of volume shrinkage and clamping force for plastic injection molding via approximate sequential optimization, *Simulation Modelling Practice and Theory*, 48 (2014) 35-44.

[7] M. W. Wang, Micro-ceramic injection molding of a multi shot micro patterned micro part, *International J. of Advanced Manufacturing Technology*, 51 (2010) 145-153.

[8] R. J. Bensingh, S. R. Boopathy and C. Jebaraj, Minimization of variation in volumetric shrinkage and deflection on injection molding of Bi-aspheric lens using numerical simulation, *J. of Mechanical Science and Technology*, 30 (11) (2016) 5143-5152.

[9] C. H. Wu and W. S. Chen, Injection molding and injection compression molding of the three-beam grating of DVD pickup lens, *Sensors and Actuators A: Physical*, 125 (2005) 367-375.

[10] G. W. M. Peter, P. J. L. van der Velden and H. E. H. Meijer, Multilayer injection molding Part2: Particle tracking in reactive molding. *International Polymer Process,* 9 (1994) 258-265.

[11] C. Maier, J. Giessauf and G. Steinbichler, Efficient production of thick-walled parts, *Kunststoffe International,* 9 (2013) 15-19, www.kunststoffeinternational.com, Document Number. PE111447.

[12] C. Hopmann, A. Neuss, M. Weber and P. Walach, Multi shot injection molding of thick-walled optical plastics parts, *Proceedings of PPS-29, AIP Conf. Proc*, 1593 (2014) 146-149.

[13] G. I. Kweon, Aspherical lens design by using a numerical analysis, *J. of the Korean Physical Society*, 51 (1) (2007) 93-103.

[14] A. W. Greynolds, Superconic and subconic surface descriptions in optical design, *Proc. SPIE.,* 4832 (2002) 1-9.

[15] H. Oktem, T. Erzurumlu and I. Uzman, Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part, *Materials & Design*, 28 (4) (2017) 1271-1278.

[16] K. Lee and J. C. Lin, Optimization of injection molding parameters for LED lampshade, *Transactions of the Canadian Society for Mechanical Engineering*, 37 (3) (2013) 313-323.

[17] T. Erzurumlu and B. Ozcelik, Minimization of warpage and sink index in injection-molded thermoplastic parts using Taguchi optimization method, *Materials & Design*, 27 (10) (2006) 853-861.

[18] G. H. R. Pundir, V. C. Chary and M. G. Dastidar, Application of Taguchi method for optimizing the process parameters for the removal of copper and nickel by growing aspergillus sp, *Water Resources and Industry* (2016) 1-10.

[19] J. C. Lin and K. S. Lee, Molding analysis of multi-cavity aspheric lens and mold designing, *Advances in Materials and Processing Technologies*, ISSN: 1662-8985, 83-86 (2009) 77-87.

[20] H. E. Lai and P. J. Wang, Study of process parameters on optical qualities for injection-molded plastic lenses, *Applied Optics*, 47 (12) (2008) 2017-2027.

[21] S. Wang, J. Ying, Z. Chen and K. Cai, Grey fuzzy PI control

for packing pressure during injection molding process, *J. of Mechanical Science and Technology*, 25 (4) (2011) 1061-1068.

[22] C. Chang, A. Chen, T. V. Lien and Y. T. Qiu, Study on injection molding of shell mold for aspheric contact lens Fabrication, *Advances in Material & Processing Technologies Conference*, *Procedia Engineering*, 184 (2017) 344-349.

[23] G. Taguchi, S. Chowdhury and Y. Wu, *Taguchi's quality engineering handbook*, Hoboken: Wiley (2005).

Min-Wen Wang is a Professor at the National Kaohsiung University of Science and Technology. His research interests include micro-molding, LIGA-like, and additive manufacturing technologies.

Fatahul Arifin is a Ph.D. candidate at the National Kaohsiung University of Science and Technology. His research interests include production engineering, plastic processing, micro injection molding, advance manufacturing technology and engineering material and technology.